# PREDETERMINATION OF CHARACTERISTICS OF ACOUSTIC EMISSION SENSORS BY ELECTRICAL RESPONSE ANALYSIS

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## INTRODUCTION

Acoustic emission (AE) is the phenomenon in which elastic or stress waves are emitted from a rapid, localized change of strain energy in a material[1]. AE sensors generate electric signals when they are stimulated by an acoustic wave. They are used for safety control of a structure and evaluation of elastic source event and material. Most of them are piezoelectric sensors employing piezoelectric elements which transform elastic signals into electric signals. AE sensors need to be chracterized before using them and the characteristics of them have been usually examined using the mechanical calibration system composed of a known elastic source and a large transmission medium. Well-defined elastic sources include small steel ball impact[2], electric spark[3], and high power laser[4] that generate delta function forces and glass capillary break[5], pencil lead break[6,7] and capacitive Coulomb force[8] that generate step function forces. Glass capillary break is known to generate step force of relatively high power and short rise time. As theoretical approach, a Green's function for an ideal elastic medium with simple geometry was studied through the utilization of the generalized ray method[9] and numerically calculated through a Fourier inversion method[10].

In the present work, as a method to characterize acoustic emission sensors, electrical responses during frequency sweeps were measured. For the present purpose, three types of typical AE sensors were fabricated. The sensors were a resonant type sensor employing a disk shape PZT element, a wide band displacement sensor employing a conical shape PZT element[11,12] and a wide band velocity sensor using PVDF(polyvinylidene fluoride) piezoelectric polymer[13]. Their electrical responses compared with sensitivity spectra that were obtained from the procedure using the mechanical calibration system.

## CALCULATION OF THEORETICAL DISPLACEMENT AND VELOCITY DUE TO SIMULATED SOURCE

The epicentral displacement of a plate corresponding to a step-like relaxation of a normal force has been theoretically determined in the previous work[5]. The vertical displacement, $U(t)$, is expressed by the convolution of a step force, $F$, and a Green's function, $G$, as follows:

$$U(t) = G * F = \int_{t_0}^{t} G(t-t')F(t')dt' \quad (1)$$

Then, the particle velocity of a plate surface is given by the derivative of the displacement with respect to time as follows:

$$V(t) = \frac{dU(t)}{dt} \quad (2)$$

The force released by glass capillary break is known as a ramp force with a rise time depending on the size of glass capillary[15]. The source function of glass capillary breaks was assumed to be described by the following equation with a parabolic rise time[16].

$$f(t) = \frac{1}{\Delta}\left\{\frac{t^2}{2} - (t-\Delta)^2 H(t-\Delta) + (t-2\Delta)^2 \frac{H(t-2\Delta)}{2}\right\} \quad (3)$$

H is a Heaviside function and $2\Delta$ is rise time.

## EQUIVALENT CIRCUITS OF PIEZOELECTRIC AE SENSORS

In the case of a resonant sensor with a piezoelectric disk of constant thickness, the resonance behavior near a resonance frequency can be represented by a simple equivalent circuit. Several separate peaks corresponding to each harmonic are found during frequency sweeps in conductance or resistance curve for a sensor — electrical response. The peaks in the electrical response correspond to separated peaks in the sensitivity spectrum of the transient output caused by a wide band source — mechanical response[14].

In the case of a wide band sensor, its sensitivity spectrum does not show separate peaks, but a flat response in a wide frequency band. This suggests that the simple equivalent circuit cannot explain the frequency spectrum of a wide band width. The wide band frequency spectrum is the superposition of an infinite series of resonant peaks, and the corresponding equivalent circuit can be regarded as a series circuit of an infinite series of simple equivalent circuits. Therefore, it seems to be possible that a mechanical response of a wide band sensor also can be similar to an electrical response which is the result to measure a resonance of a piezoelectric sensor using an electric source and a receiver.

## CONSTRUCTION OF PIEZOELECTRIC AE SENSORS

The internal structures of the fabricated AE sensors are shown in Fig.1(a), (b) and (c). Fig.1(a) shows the resonant type sensor(sensor A) fabricated using a PZT disk of diameter 12.7 mm and thickness 3.78 mm. A back-load was not used, and a wear plate was a disk of diameter 12.7 mm and thickness 0.4 mm made of white alumina($Al_2O_3$).

Fig.1(b) shows the wide band displacement AE sensor(sensor B) which has a flat response characteristic for particle displacement of a specimen surface in a wide frequency band. The active element in the sensor was a conical shape PZT element of height 3.5 mm and diameters 1 mm and 6 mm, respectively. The back load is a brass cylinder of diameter 45 mm and height 30 mm. The ribbon type silver wire was soldered in order to make measurements on non-conductive samples.

Fig.1(c) shows the wide band velocty AE sensor(sensor C) which has a flat response characteristic for particle velocity of a specimen surface in a wide frequency band. The active element of the sensor was piezoelectric PVDF polymer of thickness 110 $\mu$m and diameter 12.7 mm with gold evaporated electrodes supplied from Panwalt Co. The back loads were PVC cylinders of diameter 12.7 mm and height 30 mm whose acoustic impedance is similar to that of PVDF. A wear plate was a disk of diameter 12.7 mm and thickness 0.4 mm made of white alumina.

## EXPERIMENTAL SET-UP

The schematic diagram of the system set up to characterize the sensors is shown in Fig.2. The brittle fracture of capillary tubes made of fused quartz, 0.15 mm in inner diameter and 0.25 mm in outer diameter, was used as a step-like source force. The transmission medium of elastic waves was the steel plate of diameter 250 mm and thickness 30 mm. The indentor tip, a rod of diameter 4.65 mm made of tungsten carbide(WC), laid horizontally pressed and broke the capillary tubes against the steel plate. The transient signals excited by breaking capillary tubes were detected in the epicenter of an elastic source by a tested AE sensor. The signals from the sensors were directly recorded with 50 ns sampling rate by a digital oscilloscope, and transfered to a computer for processing.

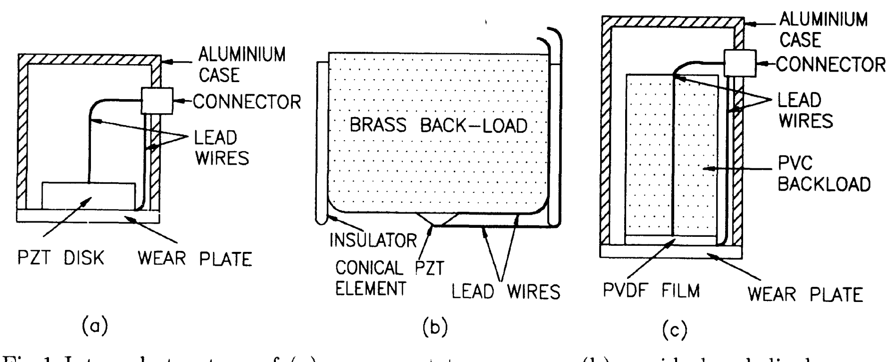


Fig.1 Internal structure of (a) a resonant type sensor, (b) a wide band displacement sensor and a wide band velocity sensor.

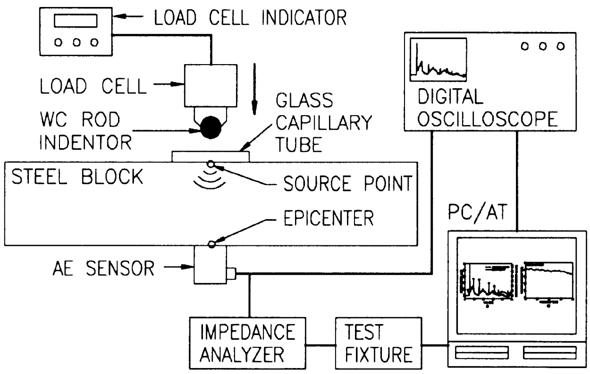


Fig.2 Schematic diagram of the system set up to measure mechanical and electrical responses of acoustic emission sensors.

The electric response, conductance during a frequency sweep, of the sensors was also measured using a HP 4192A impedance analyzer and a HP 10647A test fixture sweeping frequency with the step frequency of 1 kHz.

## TRANSIENT RESPONSE OF SENSORS WITH MECHANICAL CALIBRATION SYSTEM

Fig.3 shows the typical transient output signal from the sensor A. The output signal shows trend of the velocity-like waveform, but it shows distortion due to the resonant characteristic of the piezoelectric element.

In the case of the sensor B, the recorded signal shown in Fig.4 shows good agreement with the theoretical displacement curve. The results suggest that the sensor B is suitable for wide band displacement sensing which can make quantitative sensing of surface displacement. The calculated displacement and velocity at the epicenter as shown by dashed lines in Fig.4 and Fig.5, repectively, are the results to be calculated using the Green's function and a source time function with 300 ns rise time. The rise time of glass capillary break of 0.15 mm inner diameter and 0.25 outer diameter was reported as 300 ns[15]. In this calculation, parameters of 30 mm in the plate thickness and 5930 m/s and 3240 m/s in a longitudinal and a shear wave velocities, respectively, were used. In the figures, 'P' and 'S' designate longitudinal waves and shear waves, respectively, and the numbers before 'P' and 'S' is the number of wave modes involved in the multiple reflection. The slightly inclined angle shown in the sensor output signal near P1 wave arrival is consistent with that of the theoretical displacement curves calculated using the simulated source function.

Fig.5 shows the transient output signal from the sensor C and the theoretical surface velocity signal by the solid line and the dashed line respectively. The output signal shows good agreement with the theoretical one, especially before 5P arrival, in overall shape. This suggests that the sensor C was fabricated successfully as a wide band velocity sensor. The instants of rising of the several peaks in the recorded signal

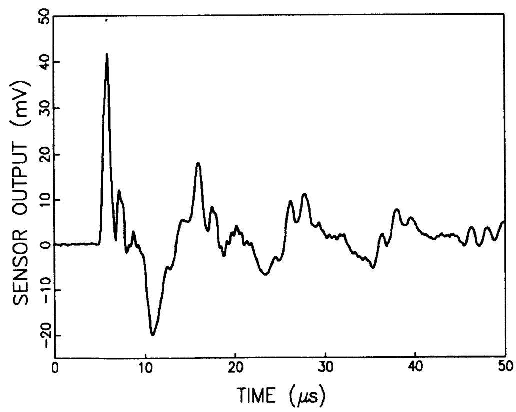


Fig.3 The transient output signal(solid line) from the resonant type sensor.

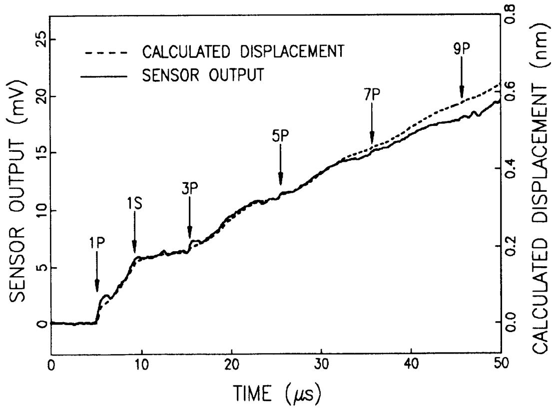


Fig.4 The transient output signal(solid line) from the wide band displacement sensor, and the calculated surface displacement signal(dashed line).

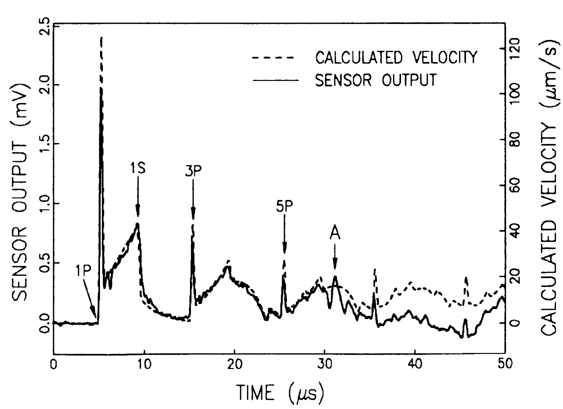


Fig.5 The transient output signal(solid line) from the wide band velocity sensor and the calculated surface velocity signal(dashed line).

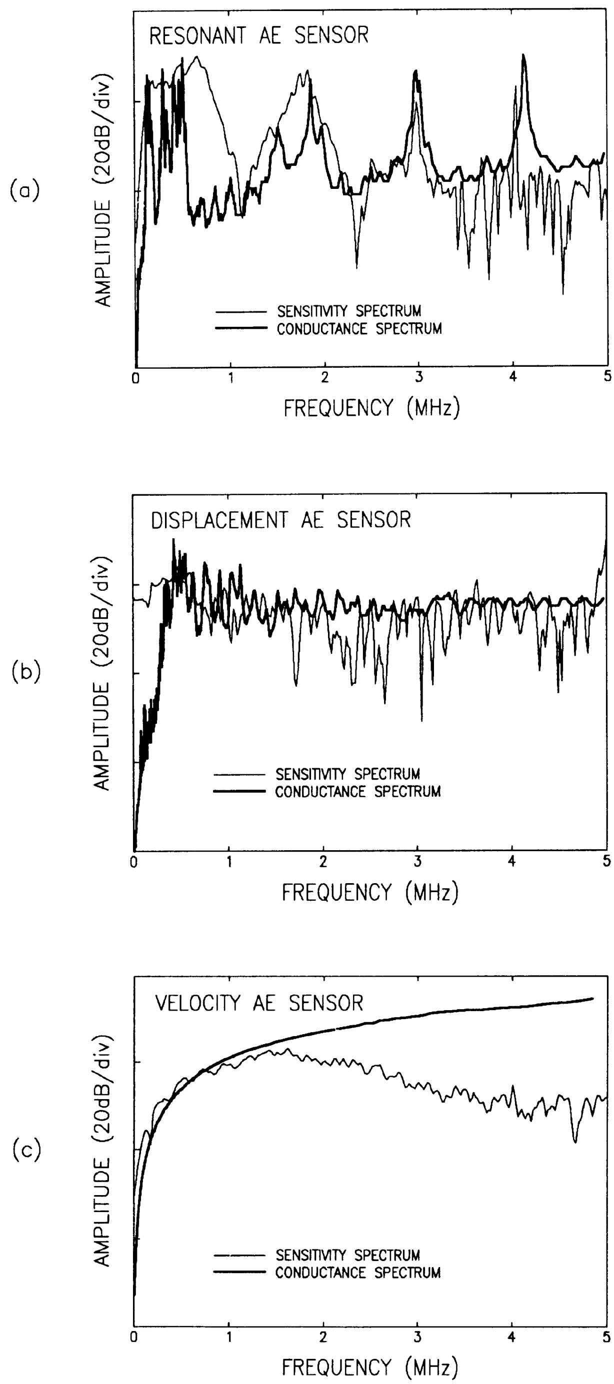


Fig.6 Sensitivity spectra(light lines) for displacement and electric conductance spectra(heavy lines) of (a) the resonant type sensor, (b) the wide band displacement sensor, and (c) the wide band velocity sensor.

exactly correspond to the arrivals of longitudinal waves, 1P, 3P, and 5P represented in theoretical one. Also the width of peak shows good agreement. This means that our simulated source function of rise time 300 ns has been well defined. The peak near 30 $\mu$s designated as 'A', different from theoretical form, turned out to be the effect of the reflection of longitudinal waves from the top surfaces of the back load.

## ELECTRICAL CONDUCTANCE AND SENSITIVITY SPECTRUM

Mechanical responses and electrical responses for three types of sensors, the resonant type sensor, the wide band diplacement sensor, and the wide band velocity sensor are shown in Fig.6(a), (b) and (c), respectively. The heavy lines indicate the variation of electric conductance with frequency and the light lines show the sensitivity spectra for displacement of the sensors obtained by comparing the frequency spectra of sensor outputs with that of theoretical displacement.

In the case of the resonant type sensor, both the sensitivity spectrum from sensor output due to simulated transient source and conductance during frequency sweep show several resonant peaks at the almost same positions. Also, in the case of the wide band displacement sensor, two responses shows similar trend not to have a resonant peak. This means that measuring electrical response can be the successful method to predetermine the characteristics of a wide band displacement sensor. The wide band velocity sensor is also showing that the sensitivity spectrum for displacement has similar trend to the electrical response signal.

## CONCLUSION

In the present work, we have shown that the characteristics of acoustic emission sensors can be determined by simple measurement of their electrical responses instead of mechanical calibration which requires several procedure. A resonant type sensor, a wide band displacement sensor and a wide band velocity sensor were fabricated. Their transient outputs due to simulated step forces and conductance during frequency sweep were measured and compared. Electric conductance spectra showed very similar trends to sensitivity spectra for displacement of three kinds of acoustic emission piezoelectric sensors.

We expect that the technique to examine electrical response of acoustic emission sensors will be utilized as a convenient method to evaluate the characteristics of acoustic emission sensors.

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